RATIOMETRIC MEASUREMENT FOR LONG TERM PRECISION, REASONING AND CASE STUDY

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Key words: Circuit-aging effects, current reference, measurement precision, offset voltage, pasteurized soft-boiled eggs, ratiometric measurement, RTD, temperature measurement, temperature sensor, thermistor, thermocouple

Abstract: A survey of modern temperature sensor types is presented. A canonical circuit for temperature measurement is analyzed with emphasis on age-induced measurement error. The circuit requires periodic calibration, which is accepted for instruments, but not for most machines that are used in different industrial processes.

A ratiometric method for temperature measurement and its implementation are introduced. The number of circuit components is minimized as much as possible. What remains, are only the effects of age-induced resistance drift. A stable precision resistor gives confidence in measurement accuracy over a period of 15 years, without periodic calibrations, which is the life time of many apparatuses.

Razmerna meritev za doseganje trajne preciznosti, argumenti in implementacija

Kjučne besede: staranje elektronskih vezij, tokovna referenca, precizna meritev, napetosni premik, pasterizirana mehko kuhana jajca, razmerna meritev, temperaturna meritev, temperaturno zaznavalo, termistor, termočlen

Izvleček: Podan je pregled polprevodniških in kovinskih temperaturnih zaznaval. Analizirana je časovna stabilnost meritve temperature z napetostno ali tokovno referenco in z meritvijo toka ali napetosti na temperaturno odvisni upornosti. Vkolikor je potrebna točnost tekom več let in so pogoji delovanja zahtevni, je spremembo napetostnega premika operacijskih ojačevalnikov v takšnem vezju potrebno kompenzirati s kalibracijo. To je uveljavljena praksa pri merilnih inštrumentih, ne pa pri napravah za robustne industrijske procese, npr. za industrijsko pripravljanja hrane.

V nadaljevanju prispevka predstavimo ratiometrično oziroma razmerno izvedbo merjenja temperature. Vplivi spreminjanja parametrov merilnega vezja so v največji možni meri izločeni. Motilni veličini meritve v predstavljeni implementaciji sta samo še vpliv staranja referenčnega upora in staranja temperaturno odvisnega upora. Po znanih podatkih o staranju uporov meritev ostane stabilna brez vmesnih kalibracij vsaj petnajst let, kar je življenjska doba strojev za industrijske procese.

1 Introduction

The contribution of this paper is in the development of a component that encapsulates the ratiometric measurement principle to achieve long-term precision. It has been developed as part of the design of a new type of an industrial kitchen appliance that produces pasteurized soft-boiled eggs. The constraints are: a) temperature error of the thermal process is to be within +-0.25 °C; and b) apparatus life lime is at least 15 years, without periodic calibrations.

The apparatus is a novelty on the market of industrial kitchen appliances. Until now, pasteurized soft-boiled eggs were not industrially produced. Domestic cooking of soft-boiled eggs does not kill salmonella, if present. Killing the bacteria, at higher temperatures, results in hard-boiled eggs.

The pasteurization and cooking of soft-boiled eggs have contradictory requirements. For the former, salmonellae, if present in the center of eggs' mass need to be unfailingly killed. For the latter, the yolk is to remain soft, i.e., coagulation is not to take place. A soft yolk requires a relatively small amount of delivered thermal energy, and the opposite is true for the destruction of salmonella in the center of the yolk. Since the two requirements are in contradiction, there have been until now no soft-boiled eggs offered in places where infection by bacteria, especially salmonella, would present a catastrophic event that could even lead to death of an elderly customer and potential law suits. A short calculation shows that pasteurized soft-boiled eggs have selling potential in breakfast restaurants of hotels, in hospitals, in homes for elderly people, as a replacement or supplement to salami and cheese.

The patented thermal process /1.2/ requires implementing a specific thermal function with temperature error less than +-0.25 °C. When regulating within +-0.25 °C, measurement imprecision is to be at most within +-0.1 °C. It is commonly understood that the market of professional kitchen appliances does not tolerate much servicing during the lifetime of a product, which is no less than 15 years. Calibration of the temperature measurement circuit every few years of operation is out of question

The problem of precise and stable temperature measurement divides into two details. One is choice of a temperature sensor; the other is design of an electronic component that converts temperature into some electrical quantity. Temperature can be measured by contact or by infrared emission, which is not addressed in this paper.

2 Contact temperature sensors

For a contact temperature sensor, one chooses amongst thermocouples, Resistance Temperature Detectors (RTDs), thermistors, and semiconductor transducers /3/. These types of sensors are built into temperature measurement devices that are built for different purposes.

When one assembles e.g. a production line he chooses among pre-built measurement devices. It is irrelevant to the designer of a new production line, which type of sensor is used in the device. The important factors are technical specification, quality, and cost.

When designing a new apparatus with common constraints on temperature measurement, it is about ease of integration and cost of the temperature measurement device.

When designing a mass-produced high-tech product where long-term measurement precision and accuracy are critical, careful selection of sensor and circuit is needed. Issues besides precision and accuracy are: responsiveness, indifference to environment disturbances, simple calibration in production, and measurement accuracy within years of product life time, if only feasible without recalibrations. Such are the constraints of the apparatus in the case study.

2.1. Thermocouple

Two wires of different metals or alloys, being connected at one side to a voltmeter, and being soldered or welded at the other side, are laid out in a temperature field with gradient, produce voltage that is proportional to the temperature difference between both wire ends, i.e., between the voltmeter and the joint. Voltage readout is a function of temperature difference between locations of the voltmeter and the joint.

Different combinations of materials produce different voltages. They are used for different temperature ranges, with different accuracies.

The American Society for Testing and Materials defines a number of commercially available thermocouple classifications in terms of performance. Types E, J, K, N, and T are base metal thermocouples, and can be used to measure temperatures from about -270 to 1372 °C. Types S, R, and B are noble-metal thermocouples, and can be used to measure temperatures from about -50 to 1820 °C /4/.

Characteristic data of most used thermocouples (types E, J, K, R, S and T) can be found in /3/. One reads that thermocouple type S (platinum with 10% rhodium vs. platinum) is used for the highest temperature range (0 °C to 1750 °C), and thermocouple type J (iron vs. constantan) has the highest accuracy (+0.1 °C). Typical values of temperature-induced voltages are in a range of some ten microvolts per degree Celsius.

A thermocouple measures temperature difference between two locations in space, one being at the joint of the two different wires, and the other being at the connector of the measuring device. In order to measure the actual temperature at the joint of the wires, one must know, and add the temperature at the location of the measuring device. This temperature is to be measured by some other means, as an absolute value and not as a temperature difference - which is the case with thermocouples.

A logical question arises at this point: if one is able to measure temperature by other means, with the same or better precision and accuracy, why add the temperature difference instead of directly measuring the temperature at the point of interest? The single most important answer is that other means of measurement can only be used over a smaller temperature range. Thermocouples, on the other hand, can be used over a wide range of temperatures. They are quite rugged. As such, they are often fastened under a screw. They can be manufactured on a spot, by either soldering or welding. If the measurement system performs the entire task of reference temperature measurement and conversion of voltage to temperature in software, using a thermocouple becomes easy: to measure temperature, one connects only a pair of wires. Thermocouple measurement is convenient when it is required to monitor many temperatures at once.

If one builds a thermocouple-based temperature transducer from scratch, he will face two challenges: a) it is challenging to linearly amplify signals in order of only some 10 microvolts because of low signal to noise ratio; and b) a solution is needed to measure the temperature at a reference location. Typical accuracy of a thermocouple is +-0.5 °C /5/.

2.2. Resistance Temperature Detector (RTD)

RTD is a synonym for a metal resistor used for temperature measurement. Metal resistance increases with temperature. Already about 1870 platinum was considered as a metal for sensing temperature. Platinum RTD (PRTD) is considered as one of most stable, linear, and accurate temperature sensors. Platinum, being a noble metal, does not react with elements of the environment, even at elevated temperatures - consequentially, it is a stable base for design of a precise and accurate temperature measurement system.

Before development of microelectronic technology, RTDs were wound up to a skeleton that was mounted within a cylinder. A seal was added at the end. Theses sensors suffered a delay /6/. Modern RTDs are produced as the deposit of a platinum film on a ceramic substrate. Each individual sensor is calibrated, i.e., laser-trimmed and sealed in casing.

All noble metals can be considered for RTDs, since they do not change internal structure at elevated temperatures. They do not react with the environment. For practical reasons, metals with higher resistance are preferred to minimize effects of parasitic resistances of wires and interconnect. Gold and silver have low resistance, tungsten is fragile, and platinum presents an optimal choice. Commercial annotations for PRTDs are PT100 and PT1000. The former has resistance of one hundred Ohms at zero degrees Celsius, the latter one thousand Ohms at zero degrees Celsius. The function of resistance versus temperature is nearly linear. For higher accuracy, polynomial coefficients are available.

A basic RTD circuit requires a constant current source for biasing and an analog instrumentation circuit (such as an instrumentation amplifier) to instrument the voltage drop across the RTD /4/.

2.3. Thermistor

Thermistors are made using semiconductor materials and can have either a Positive or Negative Temperature Coefficient (PTC or NTC, respectively). The vast majority of thermistors have a NTC.

Thermistors are more sensitive to temperature changes than metal-based sensors. In metals, resistance is proportional to temperature. In semiconductors, conductance (the amount of free electrons) is an exponential function of temperature. Small temperature changes result in high changes of resistance and the relation is nonlinear. Accuracy and long-term stability are substantially lower than for RTDs. As elevated temperatures gradually effect the distribution of dopants in a semiconductor, thermistors are not to be used above 150 °C /7/.

2.4. Monolithic linear temperature sensor

Monolithic linear temperature sensor is an integrated circuit with a built-in sensor and circuitry for signal conditioning. Output is a linear function of temperature in the form of current or voltage source, usually with 1 uA/K or 10 mV/K. The temperature range is between -55 °C and 150 °C /4/. Some of these circuits transmit temperature data in a form of serial protocol; some have only a logic output that toggles at a preset temperature.

Monolithic linear temperature sensors present an ideal design option when the simplicity of system design is crucial. Issues of a low signal-to-noise ratio and nonlinearity are solved by filtering, amplification, and linearization within the monolith. Outputs have excellent signal-to-noise ratio and values in a range that is easy to process.

Temperature measurement is based on the exponential relation of free electrons in a semiconductor to temperature. The circuit makes a logarithm of the function. The result is a linear function of temperature. Calibration constants are added. As for thermistors, these circuits are not to be used above 150 °C.

A monolithic linear temperature sensor is designed primarily for ease of usage. It is not to be used in applications of high accuracy with required long-term stability.

3 Circuits for contact temperature measurement

When measuring temperature with thermocouples, low voltages (tenths of microvolts) are to be linearly amplified by an instrumentation amplifier. When building such an amplifier, issues are low signal-to-noise ratio (low voltage on input), gain linearity, long-term stability, and robustness to environment variables (variation in power supply voltage, changes in ambient temperature). The need for accuracy requires calibration. Since thermocouples measure temperature differences, a reference temperature needs to be measured by other means. Monolithic linear temperature sensor is usually used for the purpose /3/.

Measuring temperature with a monolithic linear temperature sensor is most straightforward since the signal conditioning (amplification, filtering, linearization, and calibration) is performed within the monolithic circuit. The output can be directly connected to an A/D converter, comparator, or some serial interface.

Regarding measuring temperature with an RTD or a thermistor, they are both temperature-dependent resistors. As such, they require current or voltage excitation to produce a temperature-dependent variable (voltage or current) by Ohms' law. When processing voltage as a measure of temperature, the sensor needs to be powered by a current reference source.

Filtered and amplified voltage is a base for temperature readout. Some calculation, i.e., linearization and consideration of calibration factors is needed before the readout. Filtered and amplified voltage signal, proportional to temperature, is fed to an A/D converter (usually being an integral part of the microcontroller) and calculation is performed in the microcontroller software.

A canonical circuit for mapping temperature to voltage, by usage of an RTD or a thermistor, is in Figure 1, which is the core of the proposed circuit in /8/.

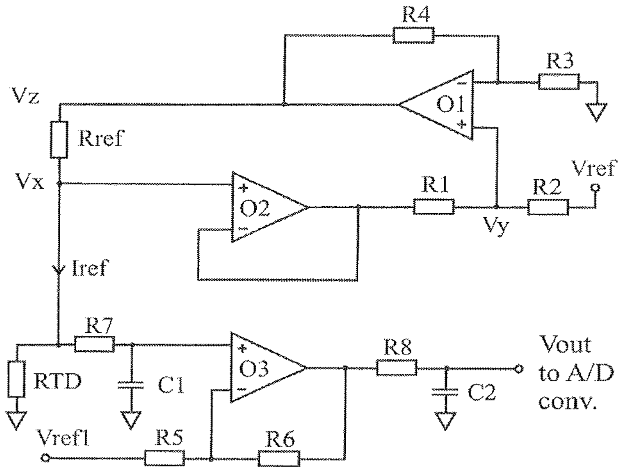

Fig. 1: RTD is powered by a current reference, voltage drop on the RTD is being filtered and amplified, by /8/.

The current reference is built from the operational amplifiers O1, O2, and from the resistors R1 to R4, and Rref. The two filters are made from the R7, C1, and from R8 and C2. The operational amplifier O3, and the resistors R5 and R6 form a gain stage.

Resistors R1, R2, R3, and R4 are of a same value. Consequentially, functionality of the current source is governed by the equations:

$$V_Z = 2V_Y = V_{ref} + V_X$$

$$V_Z - V_X = V_{ref}$$

$$I_{ref} = \frac{V_{ref}}{ref}$$

I_{ref} flows through the RTD to the ground. The corresponding voltage drop V_X on the RTD, being a function of temperature, is amplified by (1):

$$V_{out} = \frac{R_5+R_6}{R_5}\left(V_X - V_{O3\_offset} - V_{ref1}\right) \qquad (1)$$

The circuit in Figure 1 consists of three operational amplifiers, eight resistors, two capacitors and two reference voltages. Sensitivity analysis shows that the output voltage V_{out} is most sensitive to changes of V_{O3_offset} at the operational amplifier O3. V_{O3_offset} is multiplied by (R5+R6) / R5, which needs to be about 50 for proper circuit operation. A new circuit is calibrated, but years of usage do influence the electrical parameters of the circuit. Age induced drift of the O3 offset voltage, in 10 years of usage, can cause, based on manufacturers' data on time induced offset voltage drift, an error of one degree Celsius at a measurement range of one hundred degrees Celsius. Importance of time-induced one percent error depends on applications' nature.

When a relatively expensive, accurate, and time-wise stable PRTD is chosen as a sensor, then measurement quality is not to be deteriorated over years of operation by the signal conditioning circuit.

4 Ratiometric measurement

The circuit in Figure 1 is built from 13 circuit components. Each of them is prone to slight changes over years of operation. One cannot expect to build an artifact that would be completely insensitive to influence the environment. Even pyramids, which were built with all available technology of that time to last, changed over centuries.

As one looks into inner working of Nature, he notices that things are interrelated and objects are in certain relations to each other. Different organisms, from bacteria to most powerful predators, compete for their daily source of energy, for water and for space. An absolute amount of stamina is not as important as to be stronger than the competition. Outcome of fight and daily success depends on power imbalance. The power ratio counts the most in practical survival.

In sociology, humans copied these mechanisms quite fast and successfully. For example, Justitia, the Roman goddess of justice, is most often depicted with a set of weighing scales typically suspended from her left hand, upon which she measures the strengths of a case's support and opposition. In the educational process, a teacher makes a ranking of students based on a comparison of their work, not by an absolute scale.

Results of Nature observation were utilized also in some technical domains. For example, in control theory some 15 years ago principles of fuzzy regulation emerged. There, variables are exchanged for probability functions. In manufacturing, some 20 years ago emerged a bionic paradigm. There, manufacturing systems are to have capability of self-organization as different forms of life do. In integrated circuit design, required functionality depends more on ratios of dimensions and dopants than on their absolute values.

Ratiometric measurement is about inducing the measurement result from the comparison of different values. For example, an object of blue color is about blue. When it is compared to another object of blue color, one immediately notices which one is darker and which one is brighter.

4.1. Why measuring by a ratiometric method?

The answer is of a conceptual nature. A hypothesis is that the comparison system is simple enough and robust that it can effectively compare objects (variables) through its lifetime. When it is so, comparison only depends on the properties of the two objects, which are the reference and the measured object.

It is important for implementation that: a) the comparison system is designed to be most robust regarding environment disturbances and aging; and b) that the reference object changes minimally through its lifetime.

An important detail of the answer to the question, why measuring by a ratiometric method, is that such a measuring system does only comparison. This is conceptually a much simpler category than an absolute measurement.

4.2. Implementation

Usually, there are more possible implementations of a particular concept. Criterion on implementation efficiency is that equations of the implementation are to show minimal dependence on environment disturbances and on aging effects.

When precision and accuracy are important in temperature measurement, one chooses the PRTD as a temperature sensor. Logical consequence is to choose a precision resistor for a reference object. A precision resistor is to be least sensitive to temperature, moisture, and aging.

Circuit theory is explored to find means for comparing the two resistors. A working solution compares resistors by the time that is needed to discharge a capacitor via each of them.

The time needed to discharge a capacitor from voltage V_{Co} to V_C, is defined by

$$t = -RC\ln\frac{V_C}{V_{C0}} \quad (2)$$

The time *t* is measured in a digital system by counting clock ticks:

$$t = \frac{N}{f_{clk}} \quad (3)$$

For precision, clock frequency f_{clk} is to be high. Then *N* also becomes high, but the uncertainty of non-measured time within a clock period decreases. This adds to measurement precision.

If one compares capacitor discharge times, discharging the capacitor separately via R_{ref} and via *R(T)*, from the two equations above follows equation (4):

$$\frac{-R_{ref}C\ln\frac{V_C}{V_{C0}}}{-R(T)C\ln\frac{V_C}{V_{C0}}} = \frac{N_{Rref}f_{clk}}{N_{R(T)}f_{clk}} \quad (4)$$

Then,

$$R(T) = \frac{N_{R(T)}}{N_{Rref}}R_{ref} \quad (5)$$

f_{clk}, V_{Co} and V_C in (4) do cancel out. *R(T)* is calculated by (5) only from the value of a precision reference resistor and from the two discharge times. The implication is that the capacitor, the voltage comparator to V_C and the voltage reference V_{Co} can drift over time (years of operation) without affecting the measurement accuracy. In Figure 1, there are 10 circuit elements (O1, O2, O3, R1, R2, R3, R4, Rref, R5, and R6) and two voltage references (Vref, Vref1) that influence the measurement result. In equation (5), it is only the inaccuracy of measuring the two times and temperature induced drift of R_{ref} that affect the measurement..

5 Case study, implementation of ratiometric temperature measurement in the golden egg apparatus

When implementing (5) by the circuit in Figure 2, a new source of measurement uncertainty is introduced. It is resistance of the monolithic analog switches S2 and S3. As a result, equation (5) changes into (6):

$$R(T) + R_{S3} = \frac{N_{R(T)}}{N_{Rref}}(R_{ref} + R_{S2}) \quad (6)$$

To nullify measurement uncertainty that is indicated by the analog switches one has freedom to introduce a second reference resistor. Equation (5) changes to (7); circuit in Figure 2 is modified to circuit in Figure 3.

$$R(T) = \frac{N_{R(T)}-N_{Rref1}}{N_{Rref2}-N_{Rref1}}(R_{ref2} - R_{ref1}) + R_{ref1} \quad (7)$$

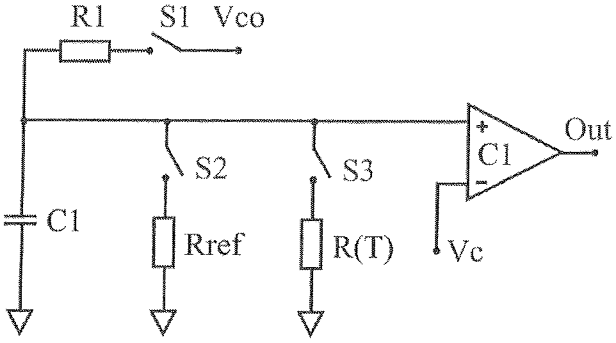

Fig. 2: The circuit to measure R(T) by the equation (5)

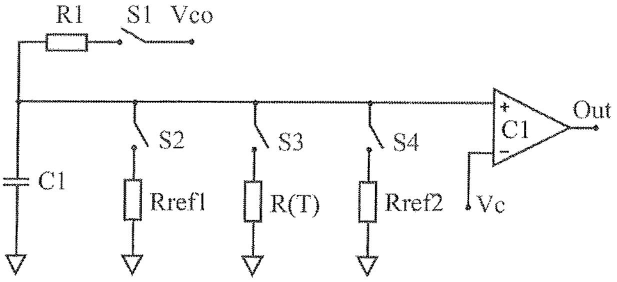

Fig. 3: The circuit that measures R(T) by the equation (7)

Taking into account resistances of switches S2 to S4, equation (7) changes to (8):

$$R(T) + R_{S3} = \frac{N_{R(T)}-N_{Rref1}}{N_{Rref2}-N_{Rref1}}(R_{ref2} + R_{S4} - R_{ref1} - R_{S2}) + R_{ref1} + R_{S2} \quad (8)$$

Since the switches S2 to S4 are part of the same analog switch monolith, one presumes that their resistances are about same. Then, equation (8) changes to (9):

$$R(T) = \frac{N_{R(T)}-N_{Rref1}}{N_{Rref2}-N_{Rref1}}(R_{ref2} - R_{ref1}) + R_{ref1} \quad (9)$$

Figure 4 shows a circuit for the implementation of (9). The encircled elements are Rref1, Rref2, C1, R1, a monolithic analog switch and two capacitors between the ground and a power supply rail.

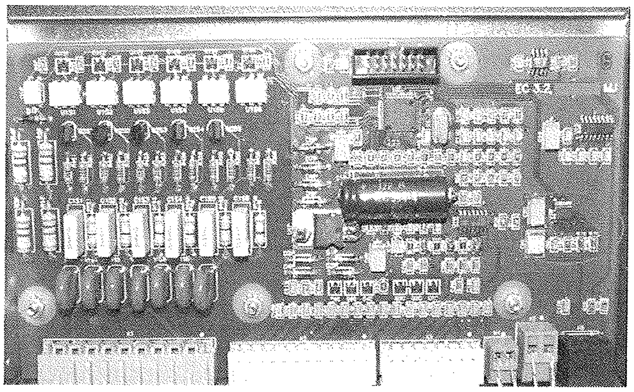

Fig. 4: Hardware of the Egg cooker control system, the temperature measuring circuit is encircled

6 Discussion

While a thermocouple is the most versatile temperature sensor and thermistor is the most sensitive, an PRTD is the most stable.

The most important factors, influencing engineering optimization in the development of the temperature sensing component in the Egg cooker in Figure 5 are: measurement accuracy, long-term stability, reliability, and ease of integration with the rest of the system.

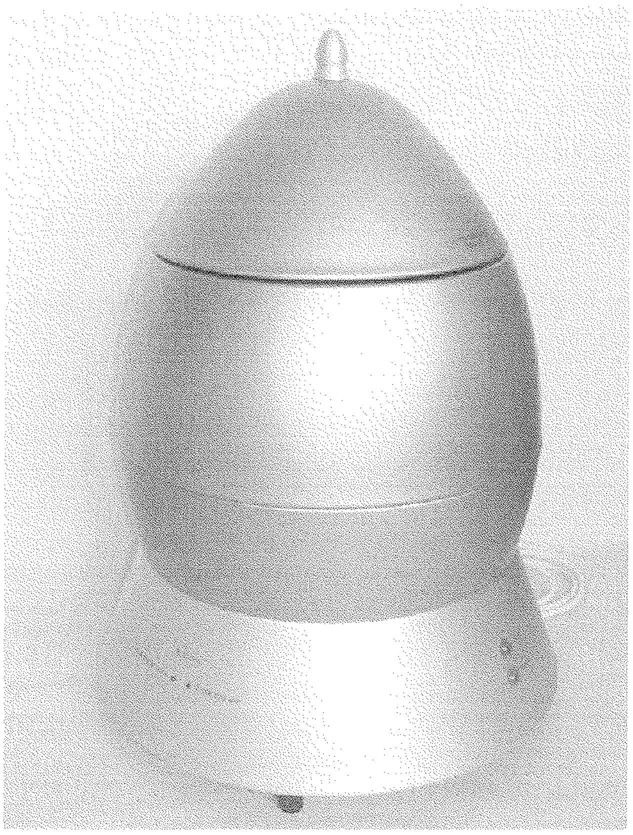

Fig. 5: Egg cooker, an industrial kitchen appliance with the precise and long-term accurate temperature regulation

Design complexity of temperature measurement is to be kept low, to minimize potential failures during the lifetime of the apparatus. In the market of professional kitchen appliances, the expected lifetime is 15 years. Servicing is reduced to elementary maintenance that is to be performed by kitchen personnel. Regular cleaning, water, and filters changing are the usual procedures. Regular calibration of temperature measuring circuit, as for measurement instruments, is not accepted for machines of industrial kitchens.

The requirement for precision of the thermal process of simultaneous pasteurization and cooking soft-boiled eggs is enormously rigorous compared to other types of cooking. The reason is the contradiction that is built into the coexistence of pasteurization and cooking of soft-boiled eggs. Pasteurization needs a high temperature and cooking soft-boiled eggs needs a low temperature. The physics of temperature distribution in eggs was studied and the thermal process was designed and patented. For the required temperature regulation within +-0.25 °C the temperature measurement accuracy of the initially calibrated system needs to stay within +-0.1 °C for the lifetime of the product.

The presented component for ratiometric temperature measurement can be used in other applications where long-term accuracy is required. The remaining issues, i.e., potential differences in resistances of analog switches, and resistance of interconnects, are nullified to greatest extent by the initial calibrations at the most important temperatures of the particular thermal process.

7 Conclusion

Characteristics of a thermocouple, an RTD, a thermistor, and a monolithic linear temperature sensor are annotated. A thermocouple is most versatile, but additional temperature measurement is needed for the reference temperature. The typical thermocouple accuracy is about +-1 °C. A thermistor is the most sensitive, which is important for fast response to a temperature change. A monolithic linear temperature sensor is simplest to integrate into an embedded control system. Both, monolith and thermistor can only be used up to 150 °C. RTDs are the most accurate and stable for the whole time of operation.

A canonic measurement circuit is built from a current reference, a filter, and a voltage amplifier. These functional blocks are made from operational amplifiers, resistors, and capacitors which all change parameters to some extent over years of operation. Time induced change of offset voltage at the operational amplifier of the gain stage affect measurement accuracy the most.

To make measurement consistently accurate over years of operation one is forced to modify the circuit. Not by fixing it, but changing it on the conceptual level. Absolute temperature measurement is changed for ratiometric measurement. The reasoning is elaborated. One of the possible ratiometric implementations is synthesized. Aging induced measurement changes are minimized on a system level to the greatest extent.

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Prispelo (Arrived): 05.10.2009 Sprejeto (Accepted): 09.06.2010